IMPACTS

An Underground Movement

Legacy

“Global warming could be one of humankind’s longest-lasting legacies. The climatic impacts of releasing fossil fuel CO_2 to the atmosphere will last longer than Stonehenge. Longer than time capsules, longer than nuclear waste, far longer than the age of human civilization so far. Each ton of coal that we burn leaves CO_2 gas in the atmosphere. The CO_2 coming from a quarter of that ton will still be affecting the climate one thousand years from now, at the start of the next millennium. And that is only the beginning.”—David Archer, 2008

Of all Earthly organisms ever to have lived, only humans have opted to travel to another celestial body. The same knowledge framework that has rocketed humans into space has revealed marvels in astronomy, biology, chemistry, geoscience, and physics. Our insights into the natural world have painted a picture of its past; the predictive powers of science and mathematics have provided visions of inevitability.

Across recorded history, powerful people have ventured to retain their influence by suppressing knowledge and distorting the truth. Creationists burn ignorance into young minds while oil-funded climate deniers tar politicians with inaction. Combatting these blights requires surprising crowds with wonders: wielding words, striking symbols, and advancing actions to inspire generations; we need indelible exhibits in public spaces.

This is a short story of our past and a cautionary tale of our future.

Hall of Wonders, 2014

Big Bang

13.798 ± 0.037 Ga

The Big Bang is a theory that describes how the Universe began. This violent natural event was not an explosion that filled dark, empty space; rather, space and time expanded rapidly, becoming less dense over time.

Albert Einstein mathed-up equations that describe gravity as spacetime curved by matter. Those equations can be re-arranged to calculate the density of the Universe at almost any point in time.

The equations reveal a smaller, denser Universe as time rolls back. This is where we get the idea that near the beginning of time, everything in the cosmos was huddled together within an ultra-dense, ultra-tiny point.

Relevance: The Big Bang produced vast amounts of hydrogen and helium with trace amounts of lithium. No other elements are thought to have existed in the Universe. Without those elements, nothing would have coalesced, much less ignited into stars.


0 m

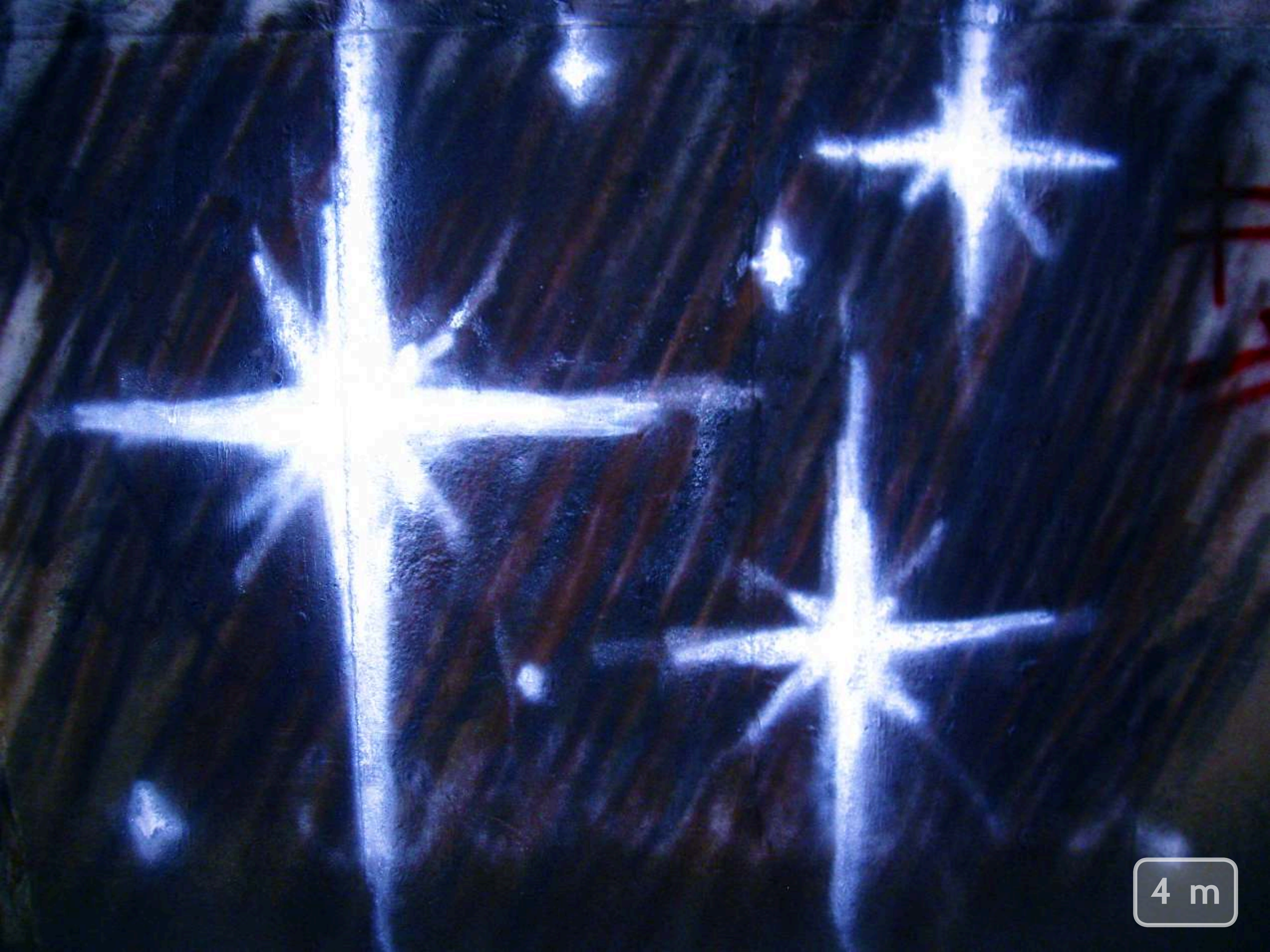
First Stars

13.643 Ga

The existence of the first stars is inferred but not yet directly observed. These stars might have formed only 155 million years after the Big Bang, possibly sooner. Many of them would have exploded as supernovae within a few million years of forming, dispersing heavier elements into intergalactic space.

Astronomers use the word metal when referring to all elements heavier than helium. The first stars are considered metal-poor while second- and third-generation stars are often considered metal-rich (high in metallicity).

Relevance: The first stars coalesced from über-massive clusters of the first elements. Those stars fused atoms into heavier elements. Later generations of stars became contaminated with those heavy elements, smelting ever-heavier atoms within their solar furnaces, ultimately making carbon, nitrogen, and oxygen: life's ingredients.


4 m

First Galaxies

13.418 Ga

Galaxies are massive collections of stars, gas, and dust. An estimated 170 billion galaxies are thought to exist in the observable Universe. The biggest of those, the giant elliptical galaxies, can contain upwards of 100 trillion stars.

That's equivalent to over 14,000 stars in one galaxy for every human alive.

Relevance: When stars explode, heavier elements are recycled into subsequent generations of stars. Without galaxies to bring stars together, heavier elements might not have so easily fused. Without those elements, life would be extraordinarily rare, if it arose at all.


10 m

First Planets

12.800 Ga

The first planets were big balls of gas called gas giants, which formed around metal-poor stars. The oldest known planet to date orbits a pair of burned-out stars and is 2.5 times more massive than Jupiter. At 5,600 light-years away, the gas giant would have no solid surface, preventing any foothold for life as we know it. If the planet has rocky moons like Jupiter's, those moons could have harboured life—life that would be long since frozen after the death of its nearest stars.

Relevance: That planets formed so soon in cosmological history, despite minimal amounts of metallicity for planetary cores, implies that planets are abundant. And wherever there are planets, life might meander.


28 m

Thin Galactic Disk

8.300 ± 1.8 Ga

The Milky Way started forming some 13.2 billion years ago as an inconceivably mega-gargantuan gas cloud of hydrogen and helium. The cloud contracted, frolicked with nearby galaxies, “borrowed” their stars, baked its own stars, then flattened. On clear, dark, moonless nights most of the faint white band we see in the sky is the Milky Way’s thin disk.

This thin disk is **326** light-years tall. Our zippiest spacecraft would take 5.7 million years to cross it, compared with a mere 73,900 years to reach the nearest star. The Milky Way spans **100,000** light-years across.

Farther out along the thin disk, elements to make dust, rocks, and asteroids decrease; that scarcity might make Jupiter-sized planets rare. Since our Jovian giants slingshot vital ice-carrying comets into the inner solar system, without those outer gas planets, life on Earth might never have taken hold.

Yet dangers abound closer to Milky Way Central, including: gravitational peturbations, supernovae, hypernovae, rogue black holes, intense cosmic radiation, increased projectiles, gamma-ray bursts, and solar system collisions. Any of those could extinguish life on Earth-like planets.

Relevance: Our home, adrift in the Milky Way’s galactic backwaters, far from the perilous galactic center, shaped our planet’s past, which may have improved life’s chances of survival.


154 m

Sun Ignites

4.567 Ga

Earth's nearest star, the Sun, started its existence with the gravitational collapse of a mind-boggingly huge gathering of hydrogen gas. The collapsing gas released a glowing red heat until the inner temperature reached roughly 10 million degrees kelvin, which ignited a fusion reaction. Like a colossal lighthouse, the Sun beat back the dark as it fused hydrogen into helium.

The Sun has since spent half its fuel. As its nuclear fuel depletes, the Sun increases in size and energy output. This will severely affect our home.

Within the next 600 million years, increased solar luminosity will reduce carbon-dioxide concentrations, ending photosynthesis forever. Between 800 million and 1.2 billion years from now Earth's rising temperature will extinguish most life, leading to the *Last Great Extinction*.

Unlike all the dinosaurs that died without ever realizing they were playing Cosmic Russian Roulette, we can predict events far into the future. Before Earth becomes a scorching hot desert wasteland, our descendants will have spread throughout the Milky Way and possibly will have parked our precious pale blue dot past Neptune, preserving all life for another four billion years.

Relevance: The Sun's light and heat enabled photosynthesis, rooting plants at the bottom of the food chain. Of equal importance, the Sun's gravity kept dust grains in its orbit. Those dust grains collided and grew over millions of years to form all eight planets, the demoted dwarf planet Pluto, and many other solar system objects.


259 m

Earth Accretion

4.540 Ga

After the Sun ignited, gravity persuaded dust particles to collide and collect, then merge into even larger rocks, asteroids, and tiny planets. The protoplanetary disk separated into rings, which sparked an era of runaway accretion (like sculpting large chunks of plasticene onto a model to embiggen it). After some 10 to 20 million years of accretion, the Earth—under its own gravity—compressed into a smaller, denser object. Both compression and radioactivity heated the Earth's interior, melting iron in the process. Iron, being one of the heaviest common elements, then sank to the planet's centre. This sinking event started slowly, then built up to epic proportions, earning it the name *Iron Catastrophe*.

The Iron Catastrophe gave Earth its overall structure: a solid iron core nestled inside a liquid iron core entombed within the mantle, blanketed by the crust (that is, huge plates floating upon the mantle).

Relevance: It is thought that the molasses-paced circulation of the liquid iron core around the solid iron core creates a dynamo. The circulating iron currents produce a magnetic field that protects life from harmful solar and cosmic radiation.


260 m

Late Heavy Bombardment

3.840 Ga

One theory states that Jupiter and Saturn combined forces to heave Neptune into a ring of outer Solar System planetismals. Neptune, having a bad-ass gravitational tug itself, destabilized the the orbits of nearby planetesimal disks, diverting wave after wave of asteroids (mostly rock) and comets (mostly ice) into the inner Solar System.

Plate tectonics and erosion erased evidence of this bombardment on Earth. But lunar evidence, such as moon rocks and its cratered surface, readily provides clues to uncover this catacalysmic past.

Relevance: Careening, ice-carrying comets pelted the early Earth, supplying it with much of the world's oceanic water, providing life a boiling pot.


280 m

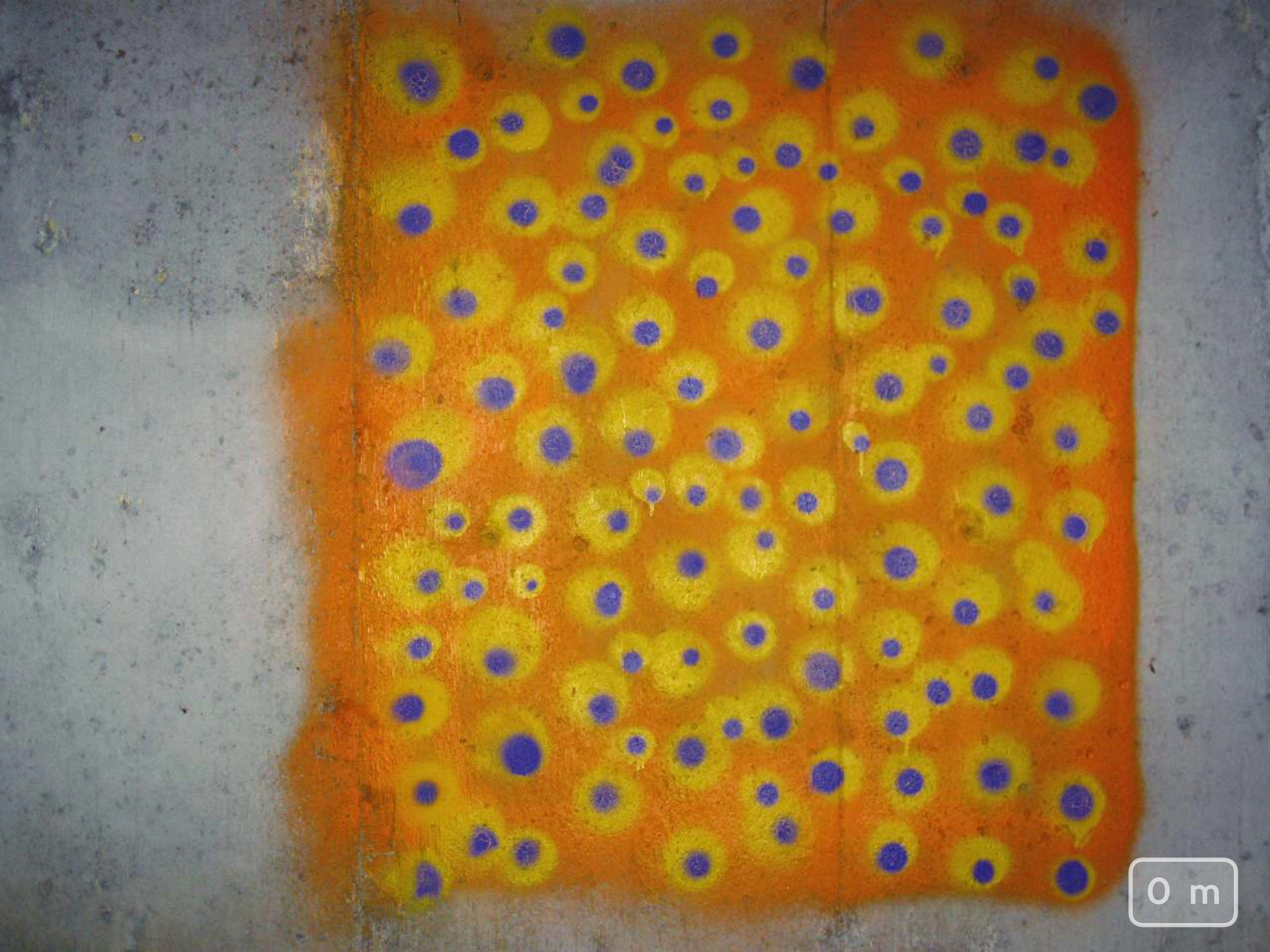
Microbial Mats

3480 Ma

Massive mats comprised of tiny bacteria provide the earliest and clearest fossilized evidence for life.

Bacteria (called prokaryotes) are survival machines with a simple cell structure. Colonizing every habitat on Earth, they have biological tricks to cause disease, consume crude oil, conduct electricity, draw solar power, and communicate with one another.

Relevance: Major early evolutionary steps, such as the development of sulfate-reducing bacteria, likely happened within such mats.


0 m

Cyanobacteria Photosynthesis

2300 Ma

Around this time saw the dawn of the *Oxygen Revolution*.

Single-celled cyanobacteria once dominated Earth. By churning out oxygen while photosynthesizing, cyanobacteria nearly extinguished all oxygen-intolerant organisms during Earth's first extinction event.

Today, cyanobacteria are found almost everywhere: oceans, fresh water, soil, dew-drenched desert rocks, and Antarctic rocks. Aquatic cyanobacteria can create extensive blooms in marine environments, appearing as blue-green scum. Such blooms can be toxic.

Relevance: Cyanobacteria created Earth's first oxygen-rich atmosphere, crucial for the advent of plants and animals.


244 m

Complex Cells

2100 Ma

A eukaryote is any critter whose complex cells contain a nucleus, organelles, and a membrane to stop its guts from spilling.

The transition that progressed from simple cells (prokaryotes) to complex cells (eukaryotes) is the most important event in the history of life on Earth, which happened a single, solitary time. (Arguably, the Big Bang is also singularly important, but let's not quibble.)

Eukaryotes probably started out as symbiotic partners living across a redox boundary of microbial mats. Reading about redox boundaries will put you to sleep—and this is a creepy place to sleep. Jumping to the point, a long time ago, one prokaryote merged with another to form a long-lasting partnership.

Relevance: The existence of eukaryotic cells allowed complex life to rise. If not for that fateful merger, the entire planetary biomass would be riddled with simple, single-celled microbes. And you wouldn't exist to yawn while reading this passage.


286 m

Multicellular Life

1200 Ma

Early multicellular organisms quite likely sprang from unicellular organisms, such as singular cells that banded together to form colossal colonies. Other theories exist, such as symbiosis through genetic chimeras. Regardless of what theory is most likely correct, life's single cell to multicellular leap has happened at least 25 times.

Relevance: Through collaboration and labour division, multicellular life exploited resources that single-celled life could not, which gave it the capacity to thrive in ecological niches unfit for simple bacteria.


473 m

Simple Animals

600 Ma

Simple animals are creatures that have few types of specialized cells. The more specialized cells that constitute a critter, the more complex it is considered. Broadly, animals can be categorised by their layers.

Early sponges were little more than small spheres one cell layer thick. They didn't—and still don't—have special tissues, organs, or ways to mambo. The only reason to consider sponges animals at all is because they cannot make their own meals and have over 10,000 different flavours.

Eventually two-layered eukaryotes evolved from sponges. The layers formed a tube that allowed early animals to ingest, digest, and stink-up the water. Moreover, these organisms unlocked the achievement of locomotion using long, whiplike cell outgrowths called flagella.

Relevance: Sponges were the first branch of life that could eat other life. Environmentally, sponges filter excess nitrogen from the water. Ecologically, sponges play a vital role in the nutrient cycles of coral reefs. Coral reefs give life places to hide and survive.


597 m

Cambrian Explosion

542 Ma

The Cambrian Era was a 10 to 20 million year period where a rapid explosion of animal diversity took place. Reasons for this velocious diversification include increased oxygen, increased calcium in seawater, rising sea levels, genetic changes, evolution of eyes, and (in time) arms races between competing species.

The discovery of many new pre-Cambrian fossils strongly suggests that the Cambrian Explosion did not start as suddenly as its name implies. Newfound transitional fossils support the idea that diversification began well before the Cambrian Era. Some think that the explosion manifested in external forms, while changes to genotype happened gradually over the preceding eons.

Regardless of what actually transpired, make time to visit the Burgess Shale in the Rocky Mountains to see the huge variety of fossilized life for yourself.

Relevance: Nearly all of today's living animals owe their existence to the unique evolutionary growth spurt during Cambrian times. Also around this time, nature finally arranged the mouth and butt-hole at opposite ends of the body, which was a Good Thing.™


609 m

Fish

518 Ma

The first ancestors of fish, or animals that were probably closely related to fish, were *Pikaia*, *Haikouichthys* (depicted), and *Myllokunmingia*.

These groups of animals formed basic features that were incrementally improved in subsequent versions. Features like: a primitive backbone, rudimentary vertebrae, a well-defined head, a definite tail, and bilateral symmetry. All primitive fish filter-fed close to the seabed and lacked jaws.

Eventually jaws evolved, sparking evolutionary branches for sharks, rays, and lobe-finned fish. The lobe-fin developed bones and muscles that operate the fin outside of the body, like super-primitive arms.

Relevance: Prehistoric lobe-finned fish adapted their strong, flexible fin to a limb morphology suitable for partially raising themselves out of the water. These early fish were the precursors of land animals from dinosaurs to humans.


614 m

Amphibians

365 Ma

Primitive amphibians (among the first tetrapods—four-limbed animals with a backbone) grew to 1.5 meters long, had a sprawling gait, and might have gorged upon unsuspecting insects that had yet to adapt land predator defenses. (Insects, being invertebrates of trilobite ancestry, evolved independently from vertebrates some 35 million years before amphibians.)

Relevance: Amphibians had lungs and gills, giving them the ability to breathe in water and on land. The changes that allowed these animals to conquer land opened new environments that would further drive adaptation.


646 m

Amniotes

312 Ma

The first fully landlubbing animals with a spine are called amniotes. These innovative vertebrates lounge atop the family tree of two key lineages: reptiles and mammals.

Relevance: Amniote eggs had a hard, semi-permeable shell that protected embryos from harsh, terrestrial environments (many millions of years before any chickens existed). The shell would later evolve into a placenta (during the late Jurassic, 160 million years ago), which was particularly advantageous because it gave developing embryos more time to develop in the relative safety of their mother's womb, among other benefits.


657 m

Dinosaurs

231.4 Ma

The first dinosaurs were small meat eaters, roughly the size of a German Shepherd. Entering the Jurassic period, some 30 million years after the dawn of the terrible lizards, dinosaurs grew in size and diversity. One of the longest herbivores ever discovered, *Argentinosaurus huinculensis*, grew 36 meters long, which is almost the same distance you walked from Cyanobacteria Photosynthesis to Multicellular Life.

Apex predator *Giganotosaurus* is thought to have attacked Argentinosaurus in packs. Sporting a maximum speed of 50 kph, its charge must have been terrifyingly ferocious. The epically titanic battles they'd have had would have been heard and felt at tremendous distances.

Most dinosaurs, though, were human-sized carnivores.

For all our dino discoveries, their longevity is unknown. Estimates of their lifespan range from 30 to over 300 years, depending on size and ability to escape (or avoid) deadly situations.

Relevance: Dinosaurs are impressive, but they are not directly linked to human evolution. It is thought that dinosaurs occupied ecological niches that oppressed mammals, forcing them to hide in the shadows of night. Given that predatory dinosaurs had to eat lots of meat, the puny mammals probably weren't worth the chase.


674 m

Mammals

208.5 Ma

Ancestral mammals, such as *Morganucodon* and *Eozostrodon*, did not and could not compete in the same ecological niches dominated by the monstrous dinosaurs that roamed the air, land, and sea. So most mammals remained mouse- or cat-sized.[1]

This led to an unexpectedly favourable plot-twist: their tiny mammalian metabolisms helped stave off starvation during the great extinction event that was to follow.

Relevance: Fashionably furry, plant-eating, milk-making, infant-suckling, warm-blooded, insect-eating, midnight-marauding, neocortex-plotting, skittishly-scampering, typically tree-dwelling beastlings.

[1] The one metre long *Repenomamus* was a notable exception that dined on dino meat.

678 m

Extinction Event

66 Ma

The Chicxulub asteroid struck Mexico's Yucatán Peninsula with a force equal to 300 million nuclear bombs. A few weeks after the impact, impenetrable clouds of dust and smoke encircled the planet and blocked out the Sun. This plunged Earth into a winter that lingered anywhere from months to years.

Without sunlight, many plants went extinct. As you might guess, this was all bad for dinosaurs and mostly bad for everything else. Large roaming herbivores that consumed those soon-scarce plants collectively decided that it was check-out time on planet Earth. Friendless, despondent, and hungry, the planet's top predators paid for a ferry ride to Deathville shortly after.

The mammals and birds that survived sustained themselves on an oh-so-savoury selection of detritus-devouring insects, worms, and snails. Yum.

Presently, Earth's extinction rate could be close to 140,000 species per year. Slowing this rapid extinction depends critically on nature reserves and conservation efforts, especially regarding tropical deforestation. Other modern anthropogenic stressors that exacerbate extinction include: ocean warming, overfishing, pollution, and acidification.

Relevance: Placental mammals evolved relatively rapidly after the dinosaurial demise from that ginormous impact.


708 m

Primates

55.8 Ma

In 2013, an international research team held a peep-show starring a miniscule, yet well-preserved fossil skeleton they named *Archicebus achilles*, considered the forebearer of all primates. Found in central China, the name of this 71 millimetre, 25 gram behemoth of a species roughly translates to “beginning long-tailed monkey, grieving tribe war hero.” Alcohol much, Fossil Finders?

Finding these pocket-sized pre-people in Asia was a kick to the pants of old school paleontologists who had erroneously convinced themselves that all primates originated in Africa. The revised theory, gradually accepted due to the steady onslaught of Asian primate fossil discoveries, now suggests that early primates probably migrated into Africa.

Relevance: Primates are generalists with an array of useful qualities. They can walk on either two or four limbs, grasp with opposable thumbs, swing through trees, use stereoscopic vision, and—for their size—have larger brains than most other mammals.


710 m

Last Common Ape Ancestor

9.88 Ma

Nakalipithecus nakayamai (the "Nakali ape") is thought to be closely related to the last common ancestor of humans, chimpanzees, and gorillas. Nakali lived in a region we now call Kenya. Its teeth, covered in thick enamel, suggest that it ate hard foods such as nuts or seeds. Thank you, Wikipedia.

We share 98.7% of our genome with chimpanzees and bonobos, 98% with gorillas, and 97% with orangutans. But the whole story is far more complex than one page could possibly relate.

Relevance: Studying the similarities and differences between ancestral apes and humans allows us to understand what makes us unique.


720 m

Power Struggle

2014 CE

"Power remains strong when it remains in the dark; exposed to sunlight it begins to evaporate."—Samuel Huntington, 1983

Earth's second atmosphere, which was mostly nitrogen and carbon dioxide (CO_2), was produced by volcanic ejections and gas-carrying asteroids during the Late Heavy Bombardment.

Throughout the Oxygen Revolution, bacteria removed and trapped CO_2 from the atmosphere while they enriched the air with oxygen. Over time those bacteria formed massive ocean-spanning algae blooms. It is from such blooms that oil and natural gas are collected.

By burning oil and natural gas, humans are pumping CO_2 back into the air at a rate unseen since the great extinction events—reversing the bacterial oxygenation process that ushered the evolutionary ascent of *homo sapiens sapiens*.

This anthropogenically released CO_2 is triggering global climate changes. Right now, increased sea levels are forcing the migration of some coastal communities. Today, oceanic acidification, overfishing, and extreme weather events are affecting the food chain, making it more difficult to feed our growing population. Soon, increased temperatures will wreak environmental havoc. Currently, wars are being waged over water.

Meanwhile, the Sun beams more free energy to our planet than we could possibly consume. When will we see the writing on the wall?

Relevance: The continued survival of life on Earth.

Power Struggle
2096